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CONFIGURATION SPACE REPRESENTATION FOR MICRO-MECHANISM FUNCTION

Elisha Sacks[1] and James Allen[2]

Computer Science Department, Purdue University[1]
Intelligent Micromachine Department, Sandia National Laboratories[2]
http://www.mdl.sandia.gov/Micromachine

ABSTRACT

This paper describes the configuration space representation of mechanical function and shows how it supports the design of micro-mechanisms. The domain characteristics of curved geometry, joint play, and custom joints render traditional design tools inappropriate, but configuration spaces can model these characteristics. They represent the quantitative and the qualitative aspects of kinematic function in a concise geometric format that helps designers visualize system function under a range of operating conditions, find and correct design flaws, study joint play, and optimize performance. The approach is demonstrated on a surface micromachined counter meshing gear discrimination device developed at Sandia National Laboratories.

KEYWORDS

MEMS, Configuration Space, Design Software

1. Introduction

Recent advances in fabrication technology make possible the synthesis of complex micro-mechanisms, such as gears, ratchets, and transmissions [1]. Designers need to analyze candidate micro-mechanisms to validate correct function, to detect design flaws, and to assess the effects of part clearances. Traditional computer-aided design software is inappropriate for these tasks. VLSI design software is not meant for moving parts. Finite element analysis is difficult and slow due to the large number of parts, the curved geometry, and the many part contact changes. It is computational overkill for designs that can be modeled as rigid-body systems. Mechanical system simulators offer an efficient alternative to finite element codes, but are limited to systems with permanent part contacts, such as pin joints, prismatic joints, and involute gears. These conditions are unrealistic for micro-mechanisms because the fabrication process cannot produce ideal joints and because changing contacts play a major role in micro-design.

We have developed a representation of mechanical function, called configuration space, that can model systems with custom joints, joint play, and contact changes. We encode the quantitative and the qualitative aspects of kinematic function in a concise geometric format that helps designers visualize system function under a range of operating conditions, find and correct design flaws, study joint play, and optimize performance. In this paper, we describe the configuration space representation and use it to model a complex micro-mechanism developed at Sandia National Laboratory. In other work, we have developed an interactive computer-aided design program that computes configuration spaces [2, 3], performs fast dynamic simulation [4], computes kinematic tolerances [5], and supports functional parametric design. We plan to use that software to design micro-mechanisms.

2. Design Example

We will discuss a prototype micro-mechanism developed at Sandia National Laboratory: a surface micro-machined counter meshing gear discrimination device [6] (Figure 1). The mechanism is a lock based on gears and ratchets. We will focus on the function of the indexing assembly. The pinion and gear rotate on fixed axes, the pawl is attached to the frame by an L-shaped spring, and the anchor is fixed to the frame. The designer intends for the pinion to rotate clockwise and to advance the gear by one tooth per rotation. Reverse gear rotation is prevented by the pawl's blocking against the anchor. Forward rotation is limited to one tooth per cycle by the damping effect of the L-shaped strut, which bends as the pawl follows the gear profile.

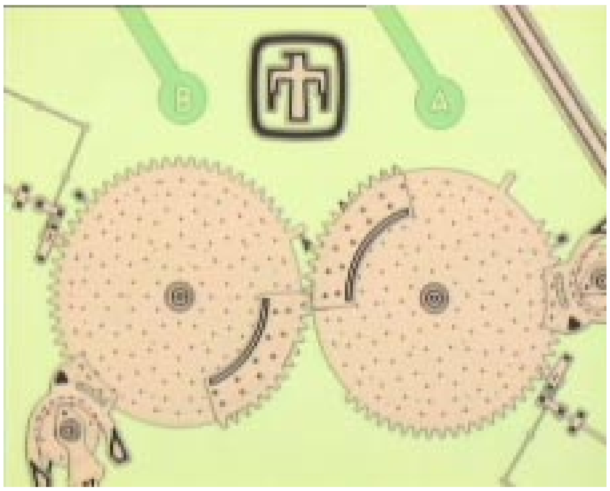

Figure 1 (a)
Photograph of surface micro-machined counter-meshing gear discriminator.

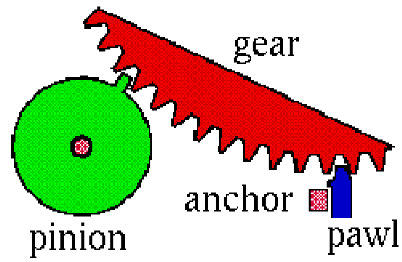

Figure 1 (b)
Detail of indexing assembly CAD model.

3. Configuration Space

We represent the kinematic function of the micro-mechanism with configuration spaces [7, 8]. We work with configuration spaces of pairs of planar parts because the micro-mechanisms that we study are nominally planar. These configuration spaces are parameter spaces whose points specify the spatial configuration (position and orientation) of interacting parts. We encode the part geometry by partitioning the configurations into three disjoint classes: blocked space where the parts overlap, free space where they do not touch, and contact space where they touch without overlap.

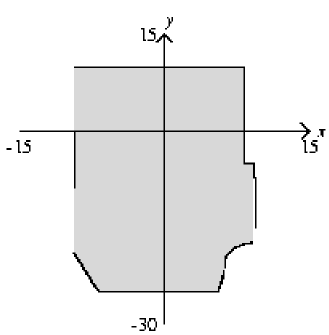

Figure 2:
Pawl/anchor configuration space

We illustrate these concepts on the pawl/anchor pair of the indexing assembly (Figure 1b). We attach reference frames to the bottom, left corner of the pawl and to the center of the fixed anchor. We assume for simplicity that the pawl translates freely, but does not rotate, so that the position of the pawl specifies the configuration of the pair. We obtain a two-dimensional configuration space whose coordinates are the Cartesian coordinates of the position vector of the pawl relative to the anchor (Figure 2). Free space is white, blocked space is grey, and contact space is black. Free and blocked space are open sets whose common boundary is contact space. Contact space is a closed set comprised of curve segments that represent contacts between part features.

The configuration space describes the kinematic function of the pair. The pawl can move freely in free space. It cannot enter blocked space. If it enters contact space, it must follow a contact curve (constrained part motion) or return to free space (break contact). The contact space geometry prescribes the motion constraints due to the various part contacts. For example, the top horizontal line represents horizontal motion due to contact between the bottom of the pawl and the top of the anchor. As the pawl moves, its configuration traces a path in configuration space that represents the motion.

Configuration spaces can encode rotation as well as translation, as we illustrate on the gear/pinion pair. We assume for the moment that the joints have no play, hence that each part has one, rotational degree of freedom. We obtain a two-dimensional, non-Cartesian configuration space whose coordinates are the part orientations (Figure 3). Contact space consists of many short contact curves that represent contacts between the pinion and the gear teeth (more precisely, between the geometric features that form the parts). The left part of the configuration space consists of narrow, slanted channels in which the part motions are coupled. As the pinion rotates clockwise, the configuration moves horizontally left until it reaches the nearest channel boundary then follows the boundary up, meaning that the gear rotates counter-clockwise. The right part of the configuration space represents the rotation of the pinion from when it exits the channel on the left (breaks contact with the gear) until it reaches the right side of the channel above.

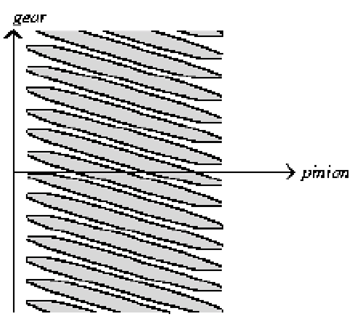

Figure 3
Gear/pinion configuration space.

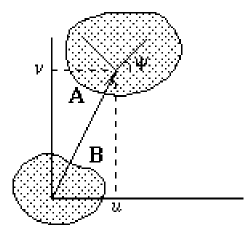

Figure 4
Three-dimensional configuration space

Figure 5
Small portion of gear/pinion configuration space with play

This analysis ignores a crucial aspect of micro-fabrication: the 0.5 micron play in every joint. This means that the pinion and the gear each has three degrees of freedom: 0.5 micron of horizontal translation relative to its hub, 0.5 micron of vertical translation, and unrestricted rotation. We need three-dimensional configuration spaces to model

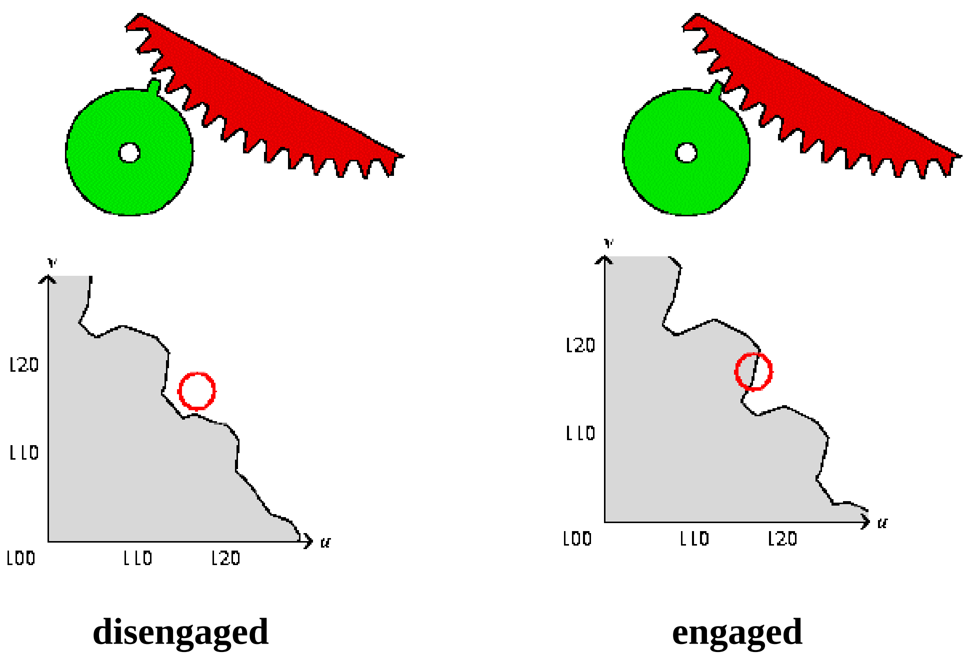

Figure 6
Cross-sections of the three-dimensional gear/pinion configuration space.

this situation. The configuration space coordinates are the position (u,v) and orientation ψ of the gear relative to the pinion (Figure 4). Figure 5 shows 1/64 of the gear/pinion configuration space. The shaded surface is contact space, the exterior is free space, and the interior is blocked space. Contact space consists of 3664 surface patches that represent the different part contacts. Although this figure is extremely complicated, we will see that we can derive a complete kinematic analysis from it.

4. Design Tools

We can validate the indexing assembly function in part by examining the configuration spaces of the interacting pairs and in part by other types of analysis (notably simulation) based on configuration space techniques. We illustrate this process on the gear/pinion pair.

The first step is to check the configuration space for correct kinematic function. The desired function is that the pinion advance the gear by one tooth per cycle. The contact space shape is consistent with this function. As the pinion rotates, the configuration enters a channel (engagement), follows it (coupled motion), and exits (disengagement) after one gear tooth. Kinematic simulation provides an alternative way of studying kinematic function. We use HIPAIR to compute the gear motion induced by constant, clockwise rotation of the pinion. The simulator computes part motions due to contacts, but ignores dynamical effects, such as friction and inertia [9]. We can animate the simulation to validate the kinematic function or can examine the motion path in configuration space.

The next step is to assess the effects of joint play on the function. We start by examining representative cross-sections of the configuration space, which quantify the play in the corresponding part orientations (Figure 6). The circles mark the range of motion due to joint play. The part play is too small to cause unintended contacts. In the disengaged orientation, the circle lies wholly in free space, which rules out other contacts that could cause chatter, vibration, and wear. In the engaged configuration, the circle center lies on the nominal contact curve and the circle does not intersect any other contact curves, which rules out backlash and jamming.

The next steps are to evaluate the mechanism dynamics via dynamical simulation and to study the functional effects of part tolerances. Although we omit these steps for lack of space, they are supported by our design software.

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